AVERAGE CURRENT MODE CONTROLLED
ENERGY STORAGE IN A DEFIBRILLATOR

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TECHNICAL FIELD

The invention relates generally to energy storage techniques for medical devices, and more particularly techniques employing switching-mode devices to store energy in an energy storage device associated with a defibrillator.

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BACKGROUND

Many devices rely on an energy storage device such as a capacitor to store potential energy and supply a voltage to a load. Examples of such devices include photographic flash lamps and flashing warning lights.

A defibrillator is another device that stores energy, typically in one or more high-voltage capacitors, and delivers the stored energy to a patient. In particular, a defibrillator

15 delivers energy to a heart that is undergoing fibrillation and has lost its ability to contract. Ventricular fibrillation is particularly life threatening because activity within the ventricles of the heart is so uncoordinated that virtually no pumping of blood takes place. An electrical pulse delivered to a fibrillating heart may repolarize the heart and cause it to reestablish a

20 normal sinus rhythm.

Although defibrillators may be internally implanted in patients that suffer from chronic fibrillation, an electric pulse may also be applied externally via paddles placed upon the patient's chest. When a switch is closed, the capacitor sends at least a part of the stored energy from paddle to paddle through the patient's chest. The energy transferred may be on

25 the order of several hundred joules. To achieve this level of energy transfer, the power needed to deliver the energy may be on the order of hundreds of kilowatts and the voltage across the capacitor may be on the order of several thousand volts.

A defibrillator such as a portable defibrillator typically includes a battery, which by itself is not capable of providing the high energy, high-voltage electric pulses required for

30 defibrillation therapy. Instead, the battery is used to charge the high-voltage energy storage capacitors. In a flyback charger, the battery supplies energy to the primary coil of a flyback

transformer while a control switch is closed. When the control switch is opened, the energy stored in the primary coil is transferred to the secondary coil of the flyback transformer. The energy is then stored on the storage capacitors, which are coupled to the secondary coil by a diode. By opening and closing the control switch, energy is incrementally transferred from

5   the battery to the capacitors, thereby increasing the energy stored in the capacitors and charging the capacitors to a high voltage.

SUMMARY

The invention relates to techniques for charging an energy storage device, such as the

10   high-voltage energy storage capacitors of an external defibrillation device, using average current mode control techniques. The time needed to charge a capacitor to a desired voltage is a function of the current flowing to the capacitor. By controlling the average current, the charge time and the voltage across the capacitor can be more effectively controlled.

Average current mode control represents a highly accurate technique for controlling

15   current in a transformer, and consequently represents a highly accurate technique for storing energy in a storage element such as a capacitor in a short time. In devices such as a defibrillator, rapid and accurate energy storage are especially advantageous. The technique may be extended to a wide range of current levels, charge times and voltage levels.

In one embodiment, the invention is directed to a method for charging an energy

20   storage device associated with a defibrillator. The method comprises applying current to a primary coil in a flyback transformer, sensing an average current through the flyback transformer, controlling the applied current to cause the average current to follow a reference current and transferring energy from the flyback transformer to an energy storage device. By controlling the applied current, the average current may be driven to follow a reference

25   current. The reference current may be a function of one or more parameters, such as energy stored in the energy storage device. When the energy storage device is a capacitor, the stored energy is related to the voltage across the capacitor.

Average current mode control represents an accurate and versatile technique for storing energy in a storage element. By controlling average current, it is possible to control,

30   for example, the time needed to charge a capacitor to a desired voltage level.

In another embodiment, the invention presents a device comprising an energy source and a charging circuit. The device charges an energy storage device associated with a defibrillator. The charging circuit transfers energy from the energy source to an energy storage device, such as a capacitor. The charging circuit includes a flyback transformer, and transfers energy as a function of the average current in the flyback transformer. The device may further comprise electrodes for delivering a defibrillation pulse to a patient and a switch that couples the electrodes to the energy storage device to deliver the defibrillation pulse to the patient.

In an additional embodiment, the invention presents a medical device comprising a transformer, an energy source that supplies energy to the primary coil of the transformer, a switch that regulates the supply of energy to the primary coil, an energy storage device that receives energy from the secondary coil of the transformer and a controller that controls the switch as a function of the average current in the transformer.

In a further embodiment, the invention presents a medical device comprising a difference circuit that generates an error signal as a function of the difference between a reference current and an average current in a transformer that transfers energy to an energy storage device. The device further includes a modulator that modulates the duty cycle of a control signal as a function of the error signal and a switch that regulates the supply of energy to a primary coil of the transformer according to the control signal. The control signal may have a constant period, which advantageously allows for management of the noise spectrum due to the control signal.

The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 is a block diagram illustrating components of a defibrillator.

FIG. 2 is a circuit diagram of a power supply, charging circuit and energy storage device for use with a defibrillator as shown in FIG. 1.

FIG. 3 is a circuit diagram illustrating a controller for average current mode control of the charging circuit of FIG. 2.

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FIG. 4 is a flow diagram illustrating techniques for storing energy using average current mode control.

DETAILED DESCRIPTION

5   FIG. 1 is a block diagram illustrating components of a defibrillator 32 formed in accordance with the present invention. Defibrillator 32 administers therapy to patient 8 via electrodes 12 and 14, which may be hand-held electrode paddles or adhesive electrode pads placed on the skin of patient 8. The body of patient 8 provides an electrical path between electrodes 12 and 14.

10   Patient electrodes 12 and 14 are coupled to switch 20 via conductors 10 and 16. Switch 20 couples patient electrodes 12 and 14 to the output of capacitor bank 22. Switch 20 is of conventional design and may be formed, for example, of electrically operated relays. Alternatively, switch 20 may comprise an arrangement of solid-state devices such as silicon-controlled rectifiers or insulated gate bipolar transistors. In each case, switch 20 should be

15   capable of carrying relatively high currents.

Capacitor bank 28 stores the energy to be delivered to patient 8. The amount of energy to be delivered may be specified by an operator via energy selector 30. Energy selector 30 supplies energy-setting information to microprocessor 26 and controls the defibrillation pulse energy to be delivered to patient 8. Energy selector 30 can be set to a

20   specific energy level by an operator, or may be set to one of a series of discrete energy levels. Defibrillator 32 may present energy selector 30 a part of a user interface which may take the form of one or more dials or switches and an interactive graphic or text display. In the case of an automated external defibrillator with preprogrammed energy levels, energy selector 30 may be eliminated.

25   Before a defibrillation pulse may be delivered to patient 8, capacitor bank 28 must be charged. Microprocessor 26 directs charging circuit 28 to charge capacitor bank 22 to a high voltage level. Charging circuit 28 delivers energy from energy source 24 to capacitor bank 22. As capacitor bank 22 stores energy, the voltage across capacitor bank 22 increases, up to a desired level. Energy source 24 may be, for example, a series of batteries or a regulated dc

30   source powered by an ac line.

The desired level of voltage across capacitor bank 22 is a function of the energy to be delivered to patient 8. The energy to be delivered is in turn a function of factors such as the energy level selected with energy selector 30 and the impedance of the body of patient 8. Defibrillator 32 may include instrumentation (not shown in FIG. 1) to measure or estimate the impedance of the body of patient 8. Because the energy to be delivered to patient 8 is a function of the voltage across capacitor bank 22, the voltage across capacitor bank 22 is controlled. As will be described below, average current mode control of a flyback charging circuit is used to quickly charge capacitor bank 22 to the desired level.

When the voltage across capacitor bank 22 reaches the desired level, microprocessor 26 may activate switch 20 to electrically connect capacitor bank 22 to patient electrodes 12 and 14, and thereby deliver a defibrillation pulse to patient 8. Alternatively, microprocessor 26 may illuminate a light or activate another indicator that informs the operator that the defibrillator is ready to deliver a defibrillation pulse to patient 8. The operator may activate switch 20 and thereby deliver a defibrillation pulse to patient 8.

Before the pulse is administered, an audible warning of the impending pulse is ordinarily given so that no one other than patient 8 will receive the defibrillation pulse. The warning may be given by the operator, for example, to admonish others to discontinue physical contact with patient 8. In the case of an automated external defibrillator, the warning may be an audible alert sounded by defibrillator 32.

Activation of switch 20 closes a circuit in which patient 8 is a part. Switch 20 may control whether defibrillation is monophasic or biphasic. The goal of defibrillation is to repolarize the heart with the current and cause the heart to reestablish a normal sinus rhythm. In some patients, one defibrillation treatment is insufficient and one or more additional defibrillation pulses may be administered. Between pulses, capacitor bank 22 must recharge to a high energy level.

In recharging capacitor bank 22, as in the initial charging, time is usually of the essence. Charging circuit 28 should charge capacitor bank 22 efficiently, quickly and accurately to a controlled voltage. Charging circuit 28 may satisfy these objectives using average current mode control of a flyback charging circuit, in accordance with the invention.

In some circumstances, energy stored in capacitor bank 22 is not to be used to administer a defibrillation pulse. For example, the patient may recover normal sinus rhythm

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and may not need another shock. In circumstances such as this, the energy in capacitor bank

22 may be discharged with energy dump 18. Energy dump 18 may include resistive elements

that receive energy from capacitor bank 22 and dissipate the energy as heat. Although

energy dump 18 is shown separate from switch 20, some applications combine the functions

5   of switch and energy dump.

FIG. 2 is a block diagram illustrating a flyback charging circuit 40 in cooperation with

a capacitor bank, represented by energy-storage capacitor C. Charging circuit 40 delivers

energy from an energy source, represented by battery V_{cc}, to capacitor C. As more energy is

delivered to energy-storage capacitor C, the potential difference V_c across energy-storage

10   capacitor C increases.

Energy is delivered from battery V_{cc} to energy-storage capacitor C via transformer 48.

Transformer 48 is modeled as ideal transformer 46, with non-ideal characteristics modeled as

additional coils on the primary side. The one additional coil represents the coupling of the

primary and secondary coils with coupling coefficient k times inductance L, or k·L. The

15   other coil models the transformer leakage inductance (1-k)·L. Ideally, k=1 and the primary

and secondary coils have unity coupling.

Transformer 48 includes a primary coil, having N_{pri} turns, and a secondary coil,

having N_{sec} turns. Current i_{pri} is supplied by source V_{cc}, flows through the primary coil and

induces current in the secondary coil. The current flowing through the secondary coil is i_{sec}.

20   Current flow is controlled by a switch, modeled as n-channel enhancement MOSFET

Q. The state of transistor Q is governed by controller 44. When controller 44 turns transistor

Q on, i_{pri} flows into the primary coil of transistor 48, causing energy to be stored in the

primary coil. When controller 44 turns transistor Q off, the energy stored in the primary coil

transfers to the secondary coil, generating current i_{sec}. Current i_{sec} flows through diode D and

25   charges energy-storage capacitor C. Diode D prevents energy-storage capacitor C from

discharging.

By turning transistor Q on and off, controller 44 supplies a series of current pulses to

energy-storage capacitor C, thereby charging energy-storage capacitor C. Because of the

non-ideal characteristics of transformer 48, a drain voltage spike may occur when controller

30   turns off transistor Q. This voltage spike, which may affect the performance of transistor Q,

is constrained by turn-off clamp circuit 42.

Energy-storage capacitor C is charged with a series of pulses. For optimal charging, however, the pulses are not of equal duration. As shown in FIG. 2, controller receives feedback and turns transistor Q on and off as a function of currents i_{pri} and i_{sec}. Currents i_{pri} and i_{sec}, which may be sensed by current sensors (not shown in FIG. 2) and fed back to controller 44, are parameters used in average current mode control. In addition, controller 44 may use the potential difference V_c across energy-storage capacitor C as a feedback parameter.

FIG. 3 is a block diagram of controller 44. Controller 44 receives currents i_{pri} and i_{sec} and provides a summer 62 that sums i_{pri} and i_{sec}, generating current i_{ave}. Current i_{ave} is the average current through transformer 48 and is, by definition, the sum of i_{pri} and i_{sec}. Controller 44 activates switch 74 to drive i_{ave} to follow a reference current, i_{ref}.

In a typical application, reference current i_{ref} is a time-varying current and not a constant current. In the embodiment shown in FIG. 3, i_{ref} depends upon the voltage V_c, but i_{ref} may depend upon parameters other than or in addition to V_c. For example, i_{ref} may vary as a function of supply voltage V_{cc}, to manage power and charge time. A current source 66 may be embodied as a processor that generates i_{ref}, or controls a variable current source that generates i_{ref}, as a function of the parameters.

The time needed to charge capacitor C to the desired level of voltage is a function of the charging current, which in turn is a function of i_{ave}. By controlling average current i_{ave}, therefore, controller 44 may quickly and efficiently charge capacitor C.

Average current i_{ave} and reference current i_{ref} are supplied to differential integrating amplifier 64, which generates error signal 76 as a function of the difference between average current i_{ave} and reference current i_{ref}. Amplifier 64 typically comprises a control feedback loop to perform the differencing function. Amplifier 64 may also include integrating elements, i.e., reactive elements, that compensate the control loop. In addition, amplifier 64 may amplify the difference between average current i_{ave} and reference current i_{ref}.

Error signal 76 may be a voltage signal or a current signal. As shown in FIG. 3, error signal 76 is a voltage signal, which is supplied as one input to comparator 70. The other input to comparator 70 is a clock signal such as periodic ramp signal 68. Clock ramp signal 68 has a fixed period, and therefore a fixed frequency. An advantage of having a fixed frequency for clock ramp signal 68 is that clock ramp signal 68 has a known noise spectrum.

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Consequently, the adverse effect of noise due to clock ramp signal 68 can be managed, such as by attenuating the noise with a filter or by generating signals at different frequencies to avoid interference with the noise spectrum of clock ramp signal 68.

The output of comparator 70 is a pulse-width modulated (PWM) signal 78. Information is encoded within PWM signal 78 in the duration of the pulses, rather than in the amplitude of the pulses. When the magnitude of error signal 76 is higher than clock ramp signal 68, the output of comparator 70 is a logically high voltage value such as 3V. Otherwise, the output of comparator 70 is a logically low voltage value such as ground potential. When the magnitude of error signal 76 is larger, the duration of the high voltage pulse generated by comparator 70 is longer. Similarly, when the magnitude of error signal 76 is smaller, the duration of the high voltage pulse generated by comparator 70 is shorter. In this way, the duty cycle of PWM signal 78 varies according to error signal 76, but the period of PWM signal 78 remains constant.

PWM signal 78 opens and closes switch 74. Switch 74 may be, for example, a field effect transistor such as n-channel enhancement mode transistor Q in FIG. 2. Switch may also be any of a number of other electronic switches. Driver 72 drives switch 74. Depending on the kind of electronic switch being driven, driver 72 may, for example, amplify, invert, or clamp PWM signal 78 to drive switch 74.

FIG. 4 is a flow diagram illustrating an embodiment of the invention. Charging begins with selection of an initial reference current i_{ref} (90), to which controller 44 will drive average current i_{ave}. As mentioned above, reference current i_{ref} ordinarily varies with time and may depend upon one or a combination of parameters.

Average current i_{ave} is, by definition, the sum of primary current i_{pri} and secondary current i_{sec} so i_{pri} and i_{sec} are summed to produce i_{ave} (92). Current sensors sense i_{pri} and i_{sec}, which may be fed back to controller 44 as currents, and may be summed by application of Kirchhoff's current law. Alternatively, current sensors may sense i_{pri} and i_{sec} and convert the currents to voltages, which may be added with the sum being representative of i_{ave}.

Amplifier 64 takes the difference between average current i_{ave} and reference current i_{ref} and generates an error signal as a function of the difference (94). Comparator 70 compares error signal 76 to clock ramp signal 68 and generates PWM signal 78 as a function of the comparison (96). Driver 72 drives switch 74 as a function of PWM signal 78 (98).

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As driver 72 drives switch 74, i_{ave} changes to follow i_{ref}. Accordingly, i_{pri} and i_{sec} change as well. Current sensors sense i_{pri} and i_{sec}, which are fed back to controller 44 (100) and are summed to produce i_{ave} (92). Through feedback, i_{ave} is driven to follow i_{ref}.

Reference current i_{ref} may change as a function of one or more feedback parameters. Voltage V_c and/or supply voltage V_{cc}, for example, may be sensed (102) and fed back to controller 44. Reference current i_{ref} may be adjusted as a function of the feedback parameter (104) and may also be adjusted as a function of other parameters.

The invention offers several advantages. Average current mode control represents a highly accurate technique for controlling current in a transformer, and consequently represents a highly accurate technique for storing energy in a storage element such as a capacitor. The accuracy extends over a wide range of current levels, and consequently, the accuracy extends over a wide range of charge times and voltage levels. In addition, the transformer may operate in a continuous mode, in which current in transformer 48 is non-zero, or a discontinuous mode, in which current in transformer 48 may reach zero. The average current may be accurately controlled in either mode. Average current control mode using a clock signal with a fixed frequency offers the additional advantage of having a known, and therefore manageable, noise spectrum.

Various embodiments of the invention have been described. These embodiments are illustrative of the practice of the invention. Although described in detail in connection with a defibrillator, the invention may find application with other devices that store energy. The invention is not limited to eternal defibrillators but may be applied to internal medical devices such as implantable cardioverters/defibrillators.

Various modifications to the apparatus or methods may be made without departing from the scope of the invention. For example, signals representative of currents such as i_{pri}, i_{sec}, i_{ave} and i_{ref} may be scaled, inverted, converted to voltages or converted to digital values. Clock ramp signal 68 need not be a ramp, but may be one of a number of other waveforms, such as a triangular wave. Switch 74 may be driven with a signal that is not a PWM signal. These and other embodiments are within the scope of the following claims.